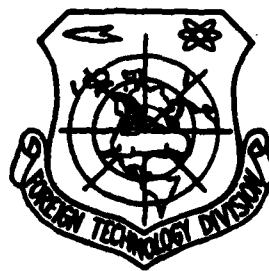# FOREIGN TECHNOLOGY DIVISION

BIOMECHANICS OF ATLANTO-OCCIPITAL AND ATLANTO-
AXIAL JOINT INJURIES

by

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BIOMECHANICS OF ATLANTO-OCCIPITAL AND ATLANTO-AXIAL JOINT INJURIES

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Scientific Research Institute of Orthopedics and Traumatology

Using the method of mathematical modeling, the article pre-
sents the biomechanics of two upper cervical vertebrae. On
the basis of an analysis of 73 patients, practical important
conclusions are proposed for the diagnosis and therapy of
changes resulting from injuries to the upper cervical seg-
ment of the spine.

Biomechanical characteristics of the atlanto-occipital and atlanto-axial
joints depend both on their function and anatomical structure. Although these
joints have been described in sufficient detail from the standpoint of their
anatomy and function in anatomy textbooks, their biomechanics have been little
investigated both under normal and pathological conditions till now. A detailed
analysis of the biomechanics of atlanto-occipital and atlanto-axial joints will
allow us to explain the mechanism giving rise to injuries in this segment of the
spine and will contribute to a more accurate diagnosis and prescription of proper
treatment.

By the method of mathematical modeling, we investigated, on anatomical speci-
mens and x-ray photographs of the upper cervical spine segment, the distribution
of forces in the atlanto-occipital and atlanto-axial joints in three planes,

namely, the frontal, sagittal, and horizontal plane under a static load induced by the action of the weight of the head and muscles in the back, and also the directed action of forces causing an injury.

We ascertained that under normal conditions, after physiological lordosis is taken into account, the main acting forces are: the weight of the head--force P_2, the force of the muscles in the neck--P_1, and the static load forces on the atlas--P' and P", induced by these forces (Fig. 1). When the elevation of the head is in equilibrium ($P_1 \cdot a = P_2 \cdot b$, according to L. P. Nikolayev), assuming that the weight of the head is $P_2 = 4.9$ kg, a/b = 0.4, the static load forces (P' + P") are 6.8 kg.

In the frontal plane, the static load forces (P' and P") are transferred from the atlanto-occipital joints to the central cervical segment of the spine in the form of the resultant force P_v (Fig. 1a) directed vertically.

In the sagittal plane (Fig. 1b) when the atlas is in a horizontal position, the force P_v, because of physiological lordosis, is directed away from the central axis of the vertebral shafts and can be considered using two components: P_0--an axial load force, which is equal to $P_v \cdot \cos C$, and P_s--a displacement force, which is equal to $P_v \cdot \sin C$ directed toward the rear, and the equivalent tension force in the transverse ligament of the atlas--R. We found out that under intermediate degree of physiological lordosis conditions at an angle $C = 5\text{--}10°$, the tension force in the transverse ligament of the atlas (R) is 0.8--1 kg. The constant action of this force in our opinion maintains a certain degree of tension in the transverse ligament, thus conditioning its shock absorbing role.

Anatomical and functional characteristics of the atlanto-axial joint depend on the absence of congruence of joint surfaces. In the equilibrium state of the first cervical vertebra, contact between the atlas and axis occurs only on the "contact crest," giving rise to the following joint angles: angle A--open toward the front, and angle B--open toward the rear. Thanks to this, the first cervical vertebra can be inclined toward the front with respect to the second vertebra by the angle A, and to the rear, by the angle B. According to Ingelmark (cited by V. G. Selivanov and M. N. Nikitin), the amplitude of front-rear inclinations of the atlas with respect to the axis is 7.5--14°.
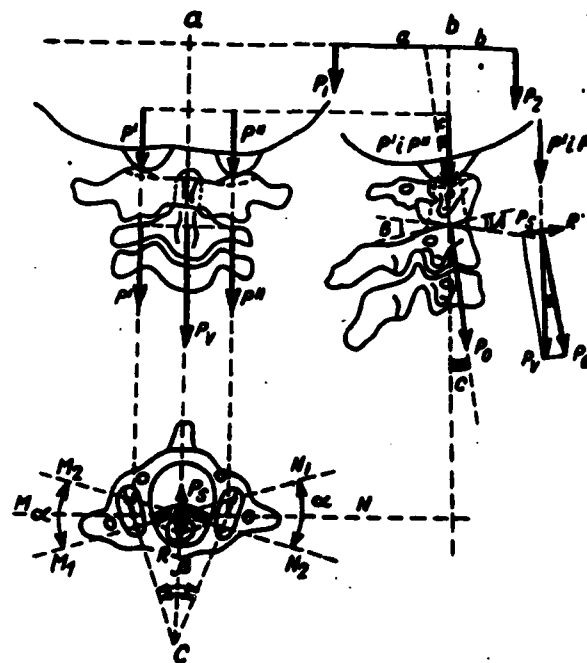
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Fig. 1. Biomechanics of atlanto-occipital and atlanto-
axial joints in three mutually perpendicular planes:
a. frontal   b. sagittal   c. horizontal

In the horizontal projection (Fig. 1c), when the position of the head is
exactly in the occipital and frontal planes, the static load forces (P' and P")
are applied to the upper joint surfaces of the atlas on the line M-N, which en-
sures equilibrium of the atlas with respect to the axis. However, since these
upper joint surfaces of the atlas with respect to each other at an angle β, which
is equal to about $40°$, the head can be turned with respect to the atlas by an
angle α, that is, by $28-30°$. A displacement of the condyle of the occipital
bone occurs along the joint surfaces of the atlas in the front-rear direction
and the static load forces are acting on the line M_1-N_1 or M_2-N_2.

Such action of the forces P' and P" during a complete turn of the atlas with
respect to the axis disturbs the equilibrium position of the first vertebra,

causing its blocking: the contact of the lateral masses of the atlas and axis no longer takes place on the "contact crest," but on the slanted portions of the joints. In our opinion, the discussed mechanism occurs in the extreme phases of a turn of the head and constitutes one of the initial stages giving rise to rotational dislocations of the atlas.

An analysis of biomechanical functional characteristics of junctions of atlanto-occipital and atlanto-axial joints has shown that the distribution of static load forces (P' and P") changes, depending on the angles of inclination of the atlas with respect to the axis in the front-rear direction (Fig. 2).
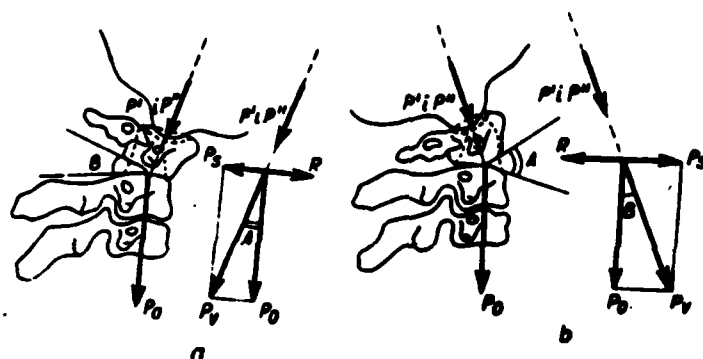
Fig. 2. Biomechanics of joints; atlanto-occipital and atlanto-axial joint in sagittal plane during inclination of atlas with respect to axis; a. inclination to front   b. inclination to rear

During inclination of the atlas to the front (Fig. 2a), the direction of the static load forces (P' + P" = P_v) is not on the axis of the spinal column, which leads to an increase in the displacement force (P_s) and a corresponding increase in the tension force of the lateral ligament of the atlas (R).

During inclination of the atlas to the rear (Fig. 2b), the displacement force (P_s) directed forward and the balancing reaction force (R) of the anterior arc of the atlas increases commensurately.

Inclination of the atlas to the front, according to our observations, under normal conditions is possible up to 13° and is limited by the tension in the rear ligaments, and in the case of injuries to these ligaments the angle of inclination can increase to 45° or a greater angle. The inclination of the atlas to the rear under pathological conditions may occur in a much smaller range, because it is limited by the tension in the anterior longitudinal ligament and the counteraction of the posterior ligaments.

Thus, the basic biomechanical characteristics of the atlanto-occipital and atlanto-axial joints under normal conditions involve changes in the distribution of static load forces at various positions of the atlas with respect to the axis. There is no doubt that the discussed biomechanical characteristics of the upper cervical spine segment constitute an essential element in an examination of various pathological states, in particular, under the effect of an injurious traumatic factor.

In order to determine more precisely the effect of the above-described biomechanical activities on the type of traumatic injuries, we investigated the injury mechanism among 73 patients with fractures and dislocations of both upper cervical vertebrae. Table I presents the type of injury and the frequency of its occurrence among our patients.

From the table it follows that dislocations of the atlas and frontal displacements of the tooth of the epistrophaeus with fracture of the arc of the atlas were observed more frequently.

A characteristic cause of indirect injury involving action of a vertical force causing dislocation and fracture of upper cervical vertebrae was a fall on the head from a height (from a vehicle with a load, from a truck during sports exercises, during a fall from a car or motorcycle)--44 patients. The group of people diving into water included ten persons. Seven people experienced a heavy object falling on their head or a blow to their head during an automobile accident. Two patients reported hitting their head from the front while riding a motorcycle, that is, during horizontal action of the force causing the injury.

Table I. Kind and frequency of injuries to upper
cervical vertebrae

Kind of injuries	Number of patients
Atlas	
Dislocation resulting from displacement of tooth of epistrophaeus	16
Displacement caused by ligament	6*
Rotational displacement	5
Bilateral fracture of posterior arc	5
Cracking fracture--dislocation of atlas	2
Axis	
Traumatic spondyloptoses	18
Dislocation of C-2	2
Fracture of tooth of epistrophaeus without displacement . . .	6
Fracture of arc	7
Chipping of fragment from anterior-inferior edge of vertebral shaft	6
Total	73

* In one case, the dislocation caused by ligament was accompanied
by fracture of the tooth of the atlas.

Thus, during an indirect injury, which has been observed by us in most cases,
the external force made direct impact on the head in the vertical or horizon-
tal direction.

A direct injury was observed by us only in 10 cases. It involved a blow
to the posterior surface of the neck, which means that the force causing the
injury was acting horizontally.

Using the method of mathematical modeling, we investigated the biomechanics
of the following joints: atlanto-occipital and atlanto-axial joints under condi-
tions in which the injury forces acted vertically and horizontally, which is
presented in Fig. 3.

From Fig. 3a it follows that the action of the vertical force causing the injury (T_c) increases the total load on the cervical segment of the spine (P_v), and therefore its components (P_s and P_o), the magnitude of which depends on the angle of inclination of the atlas with respect to the axis.

The action of horizontal forces causing an injury is shown in Fig. 3b, where T_a is a blow from the rear, and T_b is a blow from the front. This action changes only the load on the transverse ligament or the anterior arc of the atlas, and it also depends on its inclination.
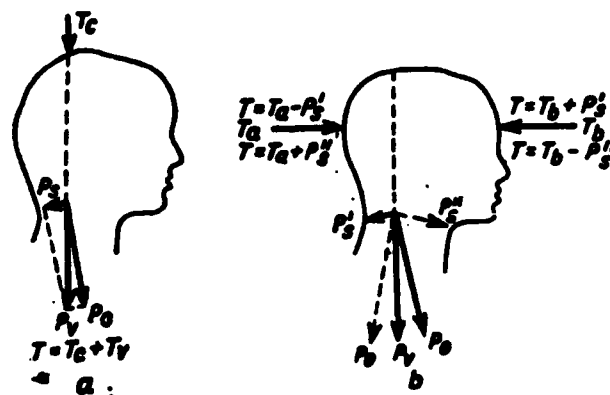

Fig. 3. Biomechanics of atlanto-occipital and atlanto-
axial joints under conditions in which forces causing
an injury are cating:
a. vertically   b. horizontally

During calculation of loads we used G. R. Graffer's and A. I. Bykhovskiy's data, according to which the force of a sudden blow increases ten times, i.e., during a fall on the head from a height of 10 m or greater height, the force of the load on the cervical segment of the spine is about 700 kg for a body weight of 70 kg; during a fall from a height corresponding to the height of a human, it is about 90 kg; and during the blow on the head when the latter weighs 5 kg, the force of the load increases to 50 kg.

The magnitude of the axial load (P_0) and the displacement force (P_s) applied to the transverse ligament of the atlas and to its anterior arc at various angles of inclination of the atlas is presented in Table II.

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From the table it follows that under normal conditions the distribution of loads on the first and second cervical vertebrae is between 0.54-6.8 kg, which obviously does not exceed the limiting strength.

During a direct blow with the head, for example, against the roof of a car (during ejection or rollover), the maximum load when the atlas is inclined to the front by 13-45°, its transverse ligament is subjected to a load from 15 to 47 kg, which may be the cause of injury due to displacement of the tooth of the epistrophaeus or a ligament injury.

During a fall on the head from the height of a human, when the atlas is inclined to the front, the load on the transverse ligament increases to 65.8 kg, and the axial load, to 95.2 kg. Hence conditions arise for injuries caused by displacements of the tooth of the epistrophaeus and by ligaments, and also traumatic spondyloptoses.

Maximum loads on the cervical spine segment occur during a fall on the head from a height exceeding the height of a human. Thus, during a fall from a height of 10 m or greater, under conditions in which the atlas is inclined to the front, the load on the anterior ligament of the tooth of the epistrophaeus can increase to 154-490 kg, and the axial load on the spine, to 700 kg. The action of such large axial and lateral loads explains the origin of traumatic spondyloptoses of the axis as a consequence of fractures of bases of its arc.

Our biomechanical studies explain why, during traumatic spondyloptoses of the second cervical vertebra, axial injuries can occur with an angle open to the front or rear; however, the decisive factor is the inclination of the atlas with respect to the axis at the moment the injury occurs.

A fact deserving attention is that the increase in the load on the anterior arc of the atlas to 154-238 kg occurs only under conditions when a fall on the head from a considerable height is combined with tilting of the head to the rear and thus inclination of the atlas with respect to the axis, to the rear, which explains the dislocations of the atlas to the rear associated with fracture of the tooth of the epistrophaeus. Mathematical calculations show that in the

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Table II. Distribution of loads on first and second cervical
vertebrae during vertical action of force causing injury
(force given in kg)

Rodzaj urazu (a)	Siły obciążenia (b)	(c) Pochylenie kręgu szczytowego w stosunku do obrotowego			
		0° (d)	fizjologiczne 5—10° (e)	ku przodowi 13°—45° (f)	ku tyłowi 13°—24°
Warunki (g) prawidłowe	Osiowa (h)	6,8	6,73—6,66	6,6—4,7	6,6—4,1
	Więzadło poprzeczne (i) kręgu szczytowego	—	0,54—1,15	1,5—4,7	—
	Łuk przedni kręgu szczytowego (j)	—	—	—	1,5—2,3
Bezpośrednie (k) uderzenie głową	Osiowa (h)	68	0,67—66,6	66—46,9	66—61
	Więzadło poprzeczne (i) kręgu szczytowego	—	5,4—11,5	15—47	—
	Łuk przedni kręgu szczytowego (j)	—	—	—	15—23
Uderzenie głową przy upadku z wysokości wzrostu człowieka (l)	Osiowa (h)	95,2	94,2—92,4	92,4—65,6	92,4—85,4
	Więzadło poprzeczne (i) kręgu szczytowego	—	7,56—16,1	21—65,8	—
	Łuk przedni kręgu szczytowego (j)	—	—	—	21—32,3
Uderzenie głową przy upadku z wysokości 10m i więcej (m)	Osiowa (h)	700	693—686	679—483	679—630
	Więzadło poprzeczne (i) kręgu szczytowego	—	56—119	154—490	—
	Łuk przedni kręgu szczytowego (j)	—	—	—	154—278

Key: a. Kind of injury
     b. Load forces
     c. Inclination of atlas with
        respect to atlas
     d. physiological
     e. to the front
     f. to the rear
     g. Normal conditions
     h. Axial

     i. Transverse ligament of atlas
     j. Anterior arc of atlas
     k. A direct blow on the head
     l. Blow on head during fall from
        height of a human
     m. Blow on head during fall from
        10 m or greater height

presence of considerable axial loads when there is inclination of the atlas with
respect to the axis, conditions are present for the Jafferson type "explosive"
fracture.

We have already established that the action of a horizontal force causing
injury changes the load on the transverse ligament or anterior arc of the atlas
(Fig. 3a), depending on its inclination with respect to the axis:

1. During a blow to the head to the rear under conditions in which the atlas
is inclined forward, the force causing the injury applied to the transverse

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ligament increases; $T = T_a - P_s'$; since $P_s' = -R$, $T = T_a' - (-R) = T_a + R$. During the same blow, however, in conditions when the atlas is inclined to the rear, the force causing the injury applied to the transverse ligament decreases: $T = = T_a + P_s''$, since $P_s'' = -R$, therefore $T = T_a + (-R) = T_a - R$.

2. During a blow to the head from the front under conditions in which the atlas is inclined to the front, the force causing the injury applied to the anterior arc decreases: $T = T_b + P_s'$, since $P_s' = -R$, $T = T_b + (-R) = T_b - R$. During the same blow, however, under conditions in which the atlas is inclined to the rear, the force causing the injury applied to the anterior arc increases: $T = T_b - P_s''$; since $P_s'' = -R$, $T = T_b - (-R) = T_b + R$.

The distribution of loads on the first and second cervical vertebrae during the action of a horizontal force causing the injury is presented in Table III.

From the table it follows that the most dangerous blows giving rise to frontal dislocations through ligaments and teeth of the vertebrae are blows in the occipital region of the head, and that blows in the forehead region are most dangerous for rear dislocations caused by the teeth of vertebrae. Inclination of the atlas with respect to the axis does not have a significant effect on the magnitude of loads on the transverse ligament and anterior arcs, because the magnitude of the forces decreases in a range which does not exceed 5 kg.

Thus, our biomechanical studies are in agreement with the results of calculations obtained during the analysis of clinical material, and confirm the direction of the force causing the injury and inclination of the atlas with respect to the axis on the type of injury in this region.

The biomechanical characteristics that were discussed must be taken into consideration in the diagnosis and therapy of injuries to the upper cervical spine segment.

In the case when the existence of an inveterate dislocation caused by a ligament is suspected, to determine the state of the transverse ligament during

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Table III. Distribution of loads on first and second cervical
vertebra under the action of horizontal force causing
injury (force given in kg)

Rodzaj urazu (a)	Siły obciążenia (b)	Pochylenie kręgu szczytowego w stosunku do obrotowego (c)			
		0°	fizjologiczne (d) 5°—10° (e)	ku przodowi 13°—24°	ku tyłowi 13°—45° (f)
Warunki prawidłowo (g)	Osiowa (h)	6,8	6,73—6,66	6,6—6,1	6,6—4,7
	Więzadło poprzeczne kręgu szczytowego (i)	—	0,54—1,15	1,5—4,7	—
	Łuk przedni kręgu szczytowego (j)	—	—	—	1,5—2,3
Uderzenie od tyłu (k) (w okolicę potyliczną)	Osiowa (h)	6,8	6,73—6,66	6,6—6,1	6,6—4,7
	Więzadło poprzeczne kręgu szczytowego (i)	68	67,4—66,8	69,5—70,3	66,5—63,3
	Łuk przedni kręgu szczytowego (j)	—	—	—	—
Uderzenie z przodu (l) (w okolicę czołową)	Osiowa (h)	6,8	6,73—6,66	6,6—6,1	6,6—4,7
	Więzadło poprzeczne kręgu szczytowego (i)	—	—	—	—
	Łuk przedni kręgu szczytowego (j)	68	69,5—69,7	66,5—65,7	69,5—72,7

Key: a. Kind of injury
      b. Load forces
      c. Inclination of atlas with
         respect to axis
      d. physiological
      e. to the front
      f. to the rear
      g. Normal conditions
      h. Axial

      i. Transverse ligament of atlas
      j. Anterior arc of atlas
      k. Blow from rear (in occipital
         region)
      l. Blow from front (in forehead
         region)

a functional x-ray examination, the chin must be brought as close as possible
to the chest, thus creating additional pressure on the ligament.

During immediate extraction because of front or rear dislocations of the
atlas, from the point of view of biomechanics, the angle must be changed, de-
pending on the kind of displacement. When the atlas is inclined to the front,
the extraction must be directed at an angle which is open toward the rear, and
when the atlas is inclined to the rear, the angle of extraction must be open
toward the front.

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In patients with traumatic spondyloptoses, the direction of the skeletal extraction must also be changed, depending on the angle of inclination of the cyst with respect to the third cervical vertebra.

Thus, the application of mathematical methods to a study of the biomechanics of upper cervical vertebrae makes possible a differentiated approach to an analysis of the kind of injuries in this region, and the prescription of appropriate therapeutic methods.

Summary

Biomechanics of the atlas and the axis in the coronal, sagittal and horizontal planes in men in normal conditions and after the action of vertical and horizontal forces of trauma was evaluated by means of mathematic modelling. It was found out that decisive influence on the biomechanics of this region had the positioning of the atlas with respect to the axis. Character of the lesion of the atlanto-occipital and atlanto-axial joints and also the tactics of treatment were explained biomechanically.

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